

## TRANSITION REGION FLUXES IN A-F DWARFS: BASAL FLUXES AND DYNAMO ACTIVITY

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### ABSTRACT

We report analysis of the transition region spectra of a sample of 87 late A and early F dwarfs and subgiants. The emission line fluxes are uniformly strong in the early F stars, and drop off rapidly among the late A stars. The basal flux level in the F stars is consistent with an extrapolation of that observed among the G stars, while the magnetic component displays the same flux-flux relations seen among the solar-like stars. Despite the steep decrease in transition region emission flux for  $B-V < 0.28$ , C II emission is detected in a Aq1 ( $B-V = 0.22$ ). The dropoff in emission is inconsistent with models of the mechanically generated acoustic flux available. We conclude that, although the non-magnetic basal heating is an increasingly important source of atmospheric heating among the early F stars, magnetic heating occurs in any star which has a sufficiently thick convective zone to generate acoustic heating.

Keywords: Transition Regions, Convection, F stars, A stars

### 1. INTRODUCTION

Stellar magnetic activity is a ubiquitous property of stars on the cool side of the H-R diagram (Ref. 1). The cool stars have deep convective envelopes in which the interaction of rotation and convection are thought to generate magnetic fields through the dynamo mechanism. On the main sequence the transition between the hot and the cool stars - in terms of activity - occurs in the late-A or early F type stars (Ref. 2). Theory predicts that stars hotter than  $B-V \approx 0.30$  do not have well-developed convective envelopes. These stars should not be able to maintain convectively-driven dynamos, nor should convectively generated noise be available to heat the atmosphere acoustically. The study of the early F and late A stars on and near the main sequence, where this transition occurs, may show us how the atmospheric heating depends on convection zone parameters.

Walter and Linsky (Ref. 3) reported on the initial results of this investigation. Wolff, Boesgaard, and Simon (Ref. 4) discussed activity in the F dwarfs based on observations

of the C IV  $\lambda 1550\text{\AA}$  and He I  $\lambda 5876\text{\AA}$  lines. Both groups show that:

- All early F dwarfs exhibit strong transition region emission, with C II and C IV surface fluxes over  $10^5 \text{ erg cm}^{-2}\text{s}^{-1}$ .
- The observed transition region flux actually increases with decreasing  $B-V$ , as the thickness of the convective envelope decreases.
- There is remarkably little scatter in the surface fluxes among the early F dwarfs ( $.3 < B-V < .42$ ), while the cooler F dwarfs exhibit solar-like rotation-activity correlations.

X-ray observations (Refs. 5 and 6) showed similar results, with all early F dwarfs being detected at essentially the same surface flux. F stars with  $B-V > 0.45$  clearly exhibit a rotation-activity correlation, while the hotter stars do not. Stars hotter than  $B-V \approx 0.30$  are not strong X-ray sources.

Walter and Schrijver (Ref. 7) show that upon subtraction of appropriate basal fluxes from the total observed emission flux, the remaining emission fluxes (the excess flux) exhibit flux-flux correlations similar to those seen in cooler stars (cf. Ref. 8.). The basal flux component may well be due to heating of the atmosphere by acoustic waves, while the rotation-activity and flux-flux correlations of the non-basal component suggest that it is due to magnetic processes similar to those observed on the Sun.

In this paper we concentrate on the behavior of the transition region fluxes in the late A stars, where the convection zone thickness becomes small.

### 2. OBSERVATIONS AND ANALYSIS

The observational data consist of deep SWP-LO observations of 87 late A and early F stars ( $0.21 \leq B-V \leq 0.53$ ). The stars are, in general, close to the ZAMS (Fig. 1), based on Stromgren uvby $\beta$  photometry (Ref. 9). None exhibit significant reddening.

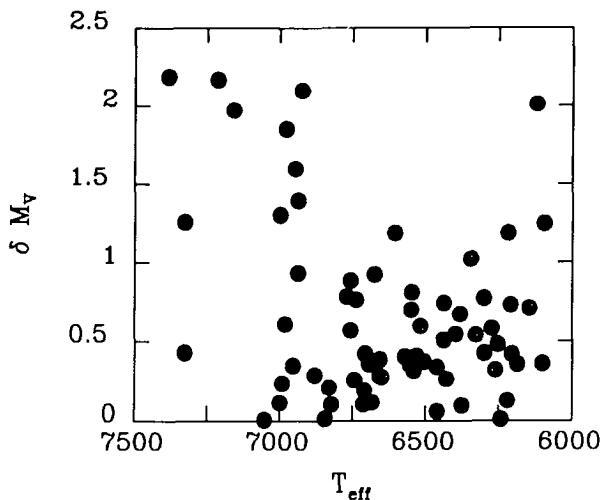


Figure 1: Distances in magnitudes above the ZAMS ( $\delta M_V=0$ ) for the 87 stars in our sample, based on the Strömgren  $\delta c_1$  parameter.

The observations were obtained during programs CCDJL, AFFJL, AFGJL, and ADIFW, with a minority of observations from the IUE archives. The spectra were well exposed in order to bring up the relatively weak transition region lines, at the expense of greatly overexposing the photospheric continuum longward of about 1600 Å (Ref. 3). Emission line fluxes are measured above a quadratic background fit through the neighboring pseudo-continuum (strongly affected by scattered light in these stars) after smoothing the data with a Fourier filter. Upper limits are deduced from the magnitude of the largest noise feature near the location of the line of interest. Surface areas are computed using the Barnes-Evans relation.

The basic data are presented in Figure 2.  $F'_{C II} \{=0.5 \times (F_{C II} + 0.63 \times F_{C IV})\}$  is a mean C II surface flux, where the factor of 0.63 accounts for the observed proportionality of C IV to C II. This averaging of the C II and C IV fluxes should reduce the random measurement errors.

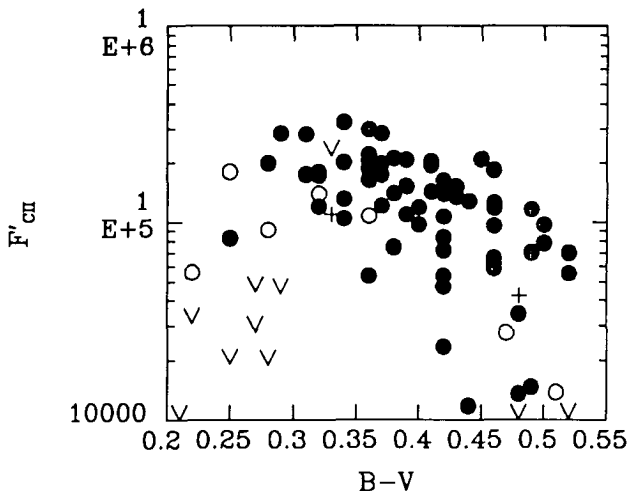


Figure 2: C II surface fluxes versus B-V. Filled circles are the mean value  $F'$ ; open circles are C II alone (C IV is overexposed); + indicates a C IV detection only (underexposed spectrum), while the inverted carets are C II upper limits.

### 3 $\alpha$ AQUILAE AND THE HOTTEST COOL STARS

We have obtained deep SWP-LO observations of 8 stars with  $0.21 \leq B-V \leq 0.27$ . Three of these yielded detections of C II  $\lambda 1335$  Å, while the rest yielded significant upper limits. There have been few reports of solar-like activity (including transition region and X-ray emission and He D<sub>3</sub> absorption) in stars hotter than  $B-V=0.29$ . One exception is  $\alpha$  Aql ( $B-V=0.22$ ), which has been detected as an X-ray source (Ref. 10), and in H I Lyman  $\alpha$  (Ref. 11). We obtained 3 deep trailed SWP-LO exposures over an interval of 10 months. The coadded spectrum, shown in Fig. 3, shows likely *emission* above the local continuum at wavelengths consistent with identification with C II  $\lambda 1335$  Å and Si IV  $\lambda 1400$  Å. These emission features are visible in the individual spectra. The C II emission feature is enhanced upon subtraction of a template A7 dwarf star composed of 2 stars from our sample with  $B-V=0.21$  and 0.22. The ratio of C II to X-ray surface flux is comparable to that observed among the early F dwarfs. For these reasons we

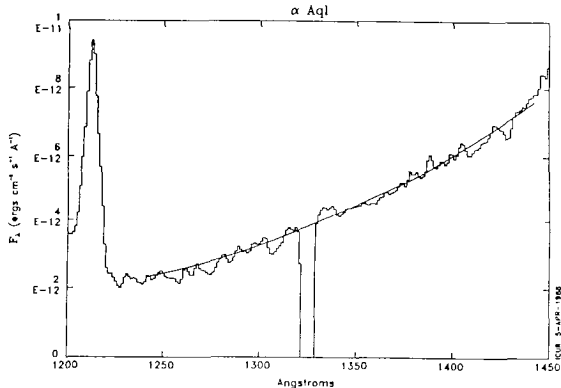


Figure 3: High S/N SWP-LO spectrum of  $\alpha$  Aql. This is the sum of 3 180s trailed exposures. Note the emission feature near the expected location of C II.

are confident that the identification of C II emission in  $\alpha$  Aql is correct.

The stars detected in C II at  $B-V=0.25$  are HD28052 and HD90132. The former is a strong X-ray source, a Hyad, and a binary with a G dwarf. The latter is an apparently single A8 dwarf. Simon and Landsman (Ref. 12) show that S3 Tau ( $B-V=0.26$ ) also exhibits strong C II emission.

### 4. FLUX-COLOR DIAGRAMS

The C II flux (Fig. 2) increases with increasing  $T_{eff}$  to  $B-V \approx 0.3$ , but drops rapidly thereafter, although significant emission is visible as far as  $B-V=0.22$ . The logarithmic range in observed CII fluxes is over an order of magnitude for  $B-V \geq 0.4$ , but only a factor of 3 for  $0.3 \leq B-V < 0.4$ . The minimum in the range is actually an artifact of the sharply increasing minimum flux level. The scatter again increases into the late A dwarfs. It is not clear how this is to be interpreted, as the limits imply a *very fast, almost instantaneous drop* in the minimum flux level while the 3 detections are consistent with a much more gradual decline. In any event, the decline in transition region heating in the

A stars is much faster than predicted by models of acoustic wave heating of the lower atmosphere (Ref. 13). The computed acoustic fluxes are overplotted on the observed transition region fluxes in Fig. 4.

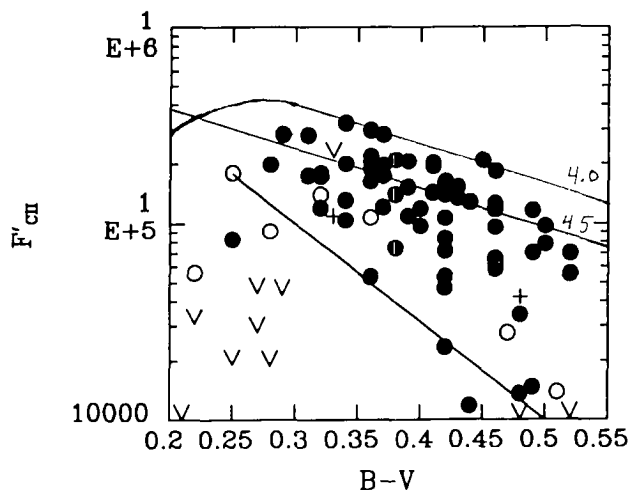


Figure 4: As Figure 2, but with the acoustic flux (Ref. 13) available overplotted. The two curves are for  $\log g = 4.0$  and  $4.5$ . The scaling is arbitrary. The shape of the computed curves matches the observed upper envelope of the transition region fluxes, but neither the lower limit (which is presumably acoustic in nature) nor the turnover in the late-A stars. Also overplotted is our preliminary estimate of the basal flux level.

## 5 FLUX-FLUX RELATIONS AND BASAL FLUXES

The power-law relations between flux densities in chromospheric, transition region, and coronal emissions have been shown to hold for late-F through early-M type dwarfs and giants, for both single stars and members of multiple systems, provided an empirical lower limit, or basal, flux density is subtracted (Ref. 14). Basal fluxes are largest for the chromospheric emissions, and likely to be negligible for the coronal X-rays. The fluxes corrected for the basal fluxes (the excess fluxes) are identified with the (magnetically) active part of the stellar atmosphere. The basal fluxes may be due to non-magnetic acoustic heating.

Since the basal component in late-A and early-F type stars is very strong, the C II and C IV excess fluxes are very sensitive to errors in the observed fluxes and colors. Walter and Schrijver (Ref. 7) demonstrated that if an empirically determined basal flux is subtracted from the observed stellar flux then the early F stars follow the relation between the X-ray and C II excess flux densities defined by cooler stars (their Fig. 2), where the basal flux correction is generally negligible. We have used here a different basal flux, an extrapolation of Rutten's C II power-law (Ref. 8) from the G stars. Although a good description of the lower envelope of the F stars, this basal flux gives poorer flux-flux correlations than did the steeper power-law used in Ref. 7. These differences point out the importance of being able to define the true basal flux accurately, as it is such a large fraction of the total flux in these stars.

## 6. CONCLUSIONS

The chromospheres and transition regions of the early F dwarfs appear to be strongly affected by the basal heating, which is uncorrelated with the X-ray emission or stellar rotation rate. The color dependence of the basal flux level (Fig. 4) is much more pronounced than the calculated variation with color of the mechanical energy generated in the upper part of the convective zone. Schrijver (Ref. 15) showed that the basal flux for the Mg II h and k lines does exhibit the color dependence expected of the acoustic flux. If the Mg II h and k and C II lower bounds both measure purely acoustic heating, then the upper chromosphere and transition region respond non-linearly to the generated mechanical flux, and hence appear to be very sensitive to changes in the photospheric and lower-chromospheric structure.

Walter and Schrijver (Ref. 7) suggested that the dynamo efficiency is suppressed at a given rotational velocity or rotational period for stars hotter than  $B-V \approx 0.4$ , although the dynamo remains operational down to  $B-V \approx 0.3$ . Because of the magnitude of the basal flux correction in the F stars, and the lack of knowledge of its true functional form, this result is questionable. Using the power-law basal flux drawn in Figure 4, we find no such decrease in dynamo efficiency from the mid- to early-F stars (Fig. 5).

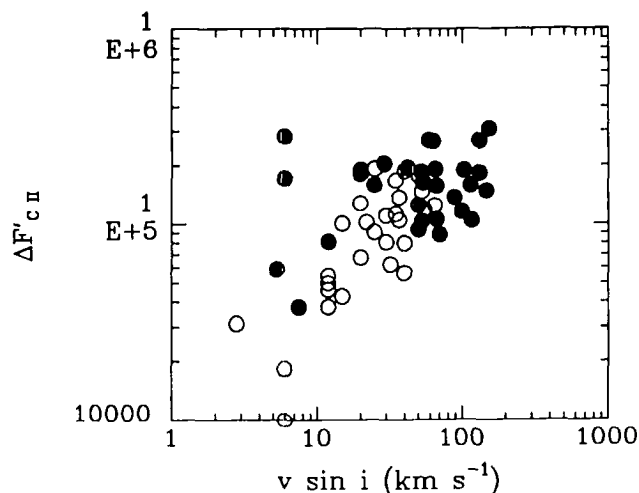


Figure 5: The mean C II flux  $F'_C$ , corrected for the basal flux, as a function of  $v \sin i$ . Solid circles are stars with  $0.28 \leq B-V \leq 0.40$ , open circles represent stars with  $0.40 < B-V \leq 0.50$ . The implied rotation-activity relation has  $F'_C \propto v \sin i^{(0.11 \pm 0.08)}$ , but an equally acceptable alternative has a steeper relation which saturates for  $v \sin i > 40 \text{ km s}^{-1}$ .

There is no dependence of the excess flux on distance above the main sequence, as shown in Figure 6, or on color (aside from the general correlation of  $v \sin i$  with  $B-V$ ).

The drop in the transition region and X-ray fluxes below  $B-V \approx 0.3$  (Refs. 1, 2, 6) suggests that with the disappearance of the convective envelope, both the basal and active heating mechanisms cease to function. Conversely, if a convective envelope is sufficiently thick to produce acoustic heating, then it seems also capable of supporting dynamo activity.

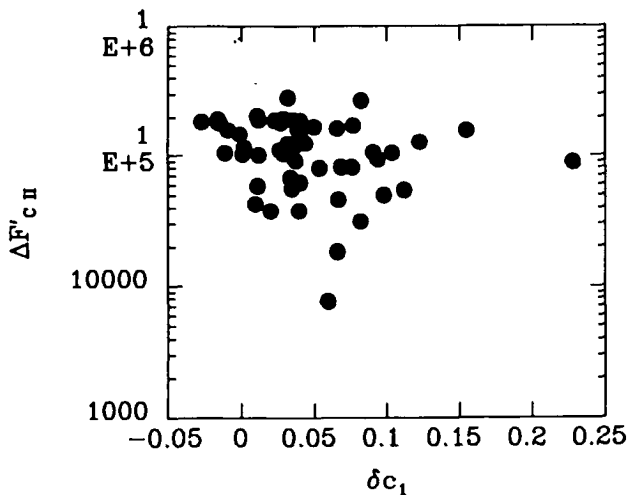


Figure 6: The scatter of  $\Delta F'_{C II}$  with the Stromgren luminosity parameter  $\delta c_1$ . No correlation of the excess flux with luminosity (or stellar evolutionary state, age, and mass) is evident.

#### 7. ACKNOWLEDGEMENTS

These data were reduced and analyzed at the Colorado RDAF, which is supported by NASA contract number NAS5-28731. This work was supported in part by NASA contract NAG5-429 to the University of Colorado.

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